Statistical Analysis of the Interdecadal Variability over the North Atlantic

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Abstract

The climate variability over the North Atlantic region is described in the 10-50 year band, using a 500-year integration of the Hamburg ECHAM1/LSG coupled general circulation model. In order to isolate nearly periodic components of the atmosphere and the ocean, the multichannel version of the singular spectrum analysis (MSSA) is applied to 11 components of the climate system. In doing so the main focus is on the turbulent exchange between the two subsystems. One interdecadal oscillation of the system ocean and atmosphere is detected with a period of about 18 years. The associated anomalies of sea level pressure (SLP) are situated east of Newfoundland while these of the geopotential height at 500 hPa are slightly shifted to the East. Both the fields undergo a primarily standing oscillation. The sea surface temperature (SST) and the sub surface temperature anomalies have a large extension along the 40° N latitude circle with most of their variability south of Newfoundland. It is found that the SST anomaly is primarily generated by the temperature advection in the upper ocean layer which is coupled to the Subpolar Gyre strength and Ekman pumping vertical velocity. Both the processes are forced by the atmosphere. In a further analysis applied only to the SST and the Geopotential height at 500 hPa over the whole Northern Hemisphere this 18 year mode was also isolated. The modes obtained by the local and hemispheric analyses are well correlated both in time and space, suggesting a more active role of atmosphere than of the ocean, in addition a strong modulation of the amplitude of the oscillation due to local processes over the North Atlantic was detected.

Zusammenfassung

Die Klimavariabilität über dem Nordatlantik wird anhand einer 500 Jahre Integration des Hamburger gekoppelten Klimamodels ECHAM1/LSG untersucht. Um periodische Komponenten in Ozean und Atmosphäre zu isolieren, wird die MSSA ("multichannel singular spectrum analysis") auf 11 Komponenten des Klimasystems angewandt. Bei den Analysen wird besonderes Augenmerk auf den turbulenten Austausch zwischen beiden Subsystemen gelegt. Es kann eine Oszillation des gekoppelten Systems mit einer Periode von etwa 18 Jahren detektiert werden. Die Anomalie des Bodendrucks weist ihre maximale Amplitude östlich von Neufundland auf, während die Anomalie des 500 hPa Geopotentials leicht östlich dazu verschoben ist. Die Anomalie der SST zeigt ihre größte Variabilität südlich von Neufundland. Diese wird im wesentlichen durch die Temperaturadvektion in der oberen Ozeanschicht generiert, welche im wesentlichen an den subpolaren ozeanischen Wirbel sowie an das "Ekman pumping" gekoppelt ist. Beide Prozesse werden durch die Atmosphäre angetrieben. In einer weiteren Analyse, in der die MSSA auf die SST und das 500 hPa Geopotential der gesamten nördlichen Hemisphäre angewandt wird, kann ebenfalls ein Oszillation von 18 Jahren detektiert werden. Diese Mode korreliert räumlich und zeitlich gut mit dem der lokalen Analyse über dem Nordatlantik, welches auf ein aktivere Rolle der Atmosphäre hinweist. Die starken Unterschiede der Amplitudenmodulation könnten durch lokale Prozesse bedingt sein.

1. Introduction

The variability of the climate system on the interdecadal time scale is a subject of increasing interest and relevance. The origins of these interdecadal variations are still discussed controversially in the literature.

On the one hand James and James (1989) discovered a long periodical oscillation in a simple atmospheric circulation model which is caused by non-linear interaction between an unstable propagating wave and a stationary wave, on the other hand Delworth et al. (1993) detected an irregular oscillation of thermohaline circulation on the time scale about 50 years. In a global coupled atmosphere-ocean general circulation model (OAGCM) they showed that this periodic fluctuation has its origin in the ocean alone. Latif and Barnett (1994) found an oscillation with a period about 20 years in a 70 year integration of the coupled ocean-atmosphere circulation model ECHO over North Pacific Ocean. They suggested a similar mechanism, first envisaged by Bjerknes (1964), after which this interdecadal variation based on an unstable air-sea interaction between the subtropical gyre circulation in the North Pacific and the Aleutian low pressure area. These results are in contradiction with Trendberth and Hurrell (1994) who showed a significant influence of the Tropics on the variability of the North Pacific region. Several authors detected fluctuations on the interdecadal time scale in a multi-century climate simulation of the Hamburg GCM ECHAM1/LSG. By using the MSSA method Robertson (1996) isolated in a 500 year integration of this GCM an oscillation with a period of about 18 years over the North Pacific region, whereby the mode in the sea temperature was forced by heatfluxes and temperature advection by the surface current. Zorita and Frankignoul (1996) found an oscillation with the period of 20 year over the North Atlantic area by using data from a shorter integration of the same model. The detected fluctuations in the SST primarily reflect the passive response of the upper ocean layer of the atmospheric forcing. There was no evidence that this mode generated by an unstable air-sea interaction.

The intention of the presented article is to investigate if air-sea interaction are responsible for interdecadal climate variability. In doing so, the multichannel version of the singular spectrum analysis (M-SSA) is applied.

2. Data

The interdecadal variation of the ocean and the atmosphere is investigated, using a 500 year integration of a coupled ocean-atmosphere circulation model (GCM). The atmospheric component of the coupled model is the Hamburg low resolution version of the ECMWF (European Center for Medium Range Weather Forecast), named ECHAM1. The horizontal resolution is limited by a triangular spectral truncation to a total wave-number 21 (T21). There are 19 vertical levels. The model and its climatology are described in detail by Cubasch et al. (1992) and von Storch (1994). The ocean component is the Hamburg LSG (Large Scale Geostrophic) model. The variables of the model are defined on an Arakawa-E-grid (Arakawa and Lamp 1977) with an effective horizontal gridsize of 4°. The vertical structure is described by 11 levels. The LSG includes a simple ice-model. The atmosphere and ocean component are coupled by fluxes of heat, mass (freshwater) and momentum (windstress). The fluxes are calculated in the atmospheric model which forces the ocean model. The SST and the ice thickness serve as lower boundary condition for the atmospheric component. The climate drift of the coupled model is reduced by using a flux correction (Sausen et al., 1988).

In order to analyze the interdecadal variability over the North Atlantic, we selected gridpoints in the area 20° N-70° N and 90° W-0° and compared the results with investigations over the entire Northern hemisphere and the North Pacific (20°N-80°N and 130°E-120°W). The analyses are based on annual averages over the years 9-508 of the GCM integration. Eleven variables of the climate system were investigated in more detail. These variables are for the atmosphere: The geopotential height at 500 hPa, the sea level pressure (SLP), the 2 meter air temperature, the fluxes of latent and the sensible heat, respectively. For the ocean: The sea surface temperature (SST), the temperature in150 meter depth, the horizontal temperature advection of the upper and the 150 meter ocean layer and the vertical part of temperature advection of the upper and the 150 meter ocean layer, which is generated by the Ekman pumping.

The annual mean of the temperature advection is given by:

$$\overline{\vec{v} \cdot \vec{\nabla} T} = \overline{\vec{v}} \cdot \vec{\nabla} \overline{T} + \overline{\vec{v}' \cdot \vec{\nabla} T'} \,, \qquad (1)$$

where the overbar denotes the annual mean and the prime its deviation from the annual means. The last term on the righthand side of equitation 1 is small compared to the first one and was neglected in the presented investigations. To be able to compare the influence of the thermal advection and the turbulent heat fluxes on the SST, it is assumed, that this influence confines to the upper ocean layer, which is equivalent to 50m depth.

The 11 components of the climate system were bandpass-filtered, retaining periods between 10 and 50 years. Due to the filter, the first and the last 25 years of the time series were truncated.

3. Analysis

The multichannel version of the singular spectrum analysis (MSSA) is described in detail by Plaut and Vautard (1994) and Robertson (1996). A fundamental property of the MSSA is its skill to detect oscillating modes in multivariate time series. A MSSA mode is accepted as an oscillation mode, if the following conditions are met:

1.) two eigenvalues are nearly equal (pairing)
2.) the two corresponding ST-EOFs are nearly periodic, they have the same period and they are in quadrature
3.) the associated PCs are in quadrature.

The main numerical difficulty using MSSA lies in the necessity to solve the eigenvalue problem for a big lagged covariancematrix. Therefore, the MSSA was applied to a reduced number of spatial variables. In doing this, at each gridpoint the time series were normalized by their standard deviation and were pooled into a combined EOF-analysis. The leading 30 PCs obtained in this combined EOF-analysis (representing 88% of the variance of the filtered data) form the input channels for the MSSA.

A fundamental problem of using the MSSA is the choice of the window length M. It essentially controls the spectral resolution and the frequency range. A window length in a neighborhood of a period of an oscillation tends to underestimate the amplitude of it (Gibbs effect). On one hand side a large window is able to distinguish between close spectral peaks, on the other hand side the temporal localization of the oscillation of the reconstructed signal is inferior. In our studies a window length of M=50 years was used. This enables us to detect periodic components in the frequency range 1/M - 5/M (Plaut and Vautard, 1994).

Figure 1a shows the eigenvalue spectrum resulting the MSSA-analysis of the leading 30 PCs of the combined EOF-analysis described above for the North Atlantic region. It could be seen that The first and the second eigenvalue are nearly equal, and clearly stand out from the rest of the spectrum. The 95% confidence interval of an eigenvalue is calculated by a heuristic variance formula given by Vautard et al. (1992). Eigenvalue 1 and 2 explain about 11 % of the variance of the filtered data. Figure 1b and 1c shows the first channel of the corresponding ST-

EOFs and T-PCs. Both are periodic and in phase quadrature. So they meet the conditions mentioned above. The period of the isolated oscillation can be estimated from the temporal behavior of the ST-EOFs in figure 1b. In that case, the detected oscillation has a period about 17.8 years.

Reconstruction of the signal in geometrical space

A special reconstruction procedure described in Plaut and Vautard (1994) allows to investigate the temporal and spatial structure of this oscillation. Figure 2 shows these reconstructed components (RCs) for a) the SST averaged over the region south of Newfoundland (45°-50°N, 55°-65°W) (gray line) and b) the geopotential height at 500 hPa averaged over the region east of Newfoundland (40°-50°N, 45°-55°W) (black line). Both areas exhibit the maximal variance in the respective variables. One can see that the amplitudes of the RCs of these two fields are strong around the year 200 and are weak around the year 150. This intermittent character of the oscillation was also found for the North Pacific by Robertson (1996), but the years with stronger and lower variability differ from these investigations. The maximal SST variation is about 0.2 K, the geopotential varies at about 5 gpm. The ratio of these fields is about 25 gpm/K and is similar to that found for the North Pacific by Robertson (1996) for the same GCM experiment. Palmer and Sun (1985) also found a similar ratio of SST and geopotential in a 50 day wintertime integration of a 5 level GCM forced by an observed SST anomaly south of Newfoundland.

Composite maps

To investigate the temporal and spatial behavior of the oscillation we construct a representative cycle using a phase composite method. We selected all times when the reconstructed SST index (showing in Figure 2) has the maximal slope and composited 10 years of either side of each time. Figure 3 shows the results of these composites for the SST south of Newfoundland and the geopotential height at 500 hPa east of Newfoundland. Both are nearly sinusoidal. The geopotential leads the SST by about 2 years. Robertson (1996) found the same behavior in the North Pacific region, where the 500 hPa geopotential height leads the SST by about 1 year.

4. Results

The 18 year mode over the North Atlantic

Figure 4a shows the composite map of the SLP at year -6 two years before the SST anomaly south of Newfoundland reaches its peak. The SLP undergoes a primarily standing oscillation in form of a dipole, with a strong low pressure area east of Newfoundland with a maximal amplitude of about 40 hPa and a weaker high pressure area in the subtropical North Atlantic. This pattern looks similar to the 500 year average of the SLP. The situation 4 years later (nearly a quarter period) is shown in figure 5b. The low has split into two parts and the high pressure area is reduced. Whereby a part has propagated to the East, another part to the West. The geopotential height at 500 hPa exhibits nearly the same spatial structure as the SLP, but the anomalous low is shifted somewhat westward with respect to the anomalous surface low (not shown). It is obvious, that an anomalous low situated east of Newfoundland causes a grater meridional gradient of the zonal windstress, which affects the subpolar and subtropical gyre circulation and the Ekman pumping vertical velocity in the ocean.

Figure 5a shows the composite map of the SST at the year -4. The highest variability is concentrated south of Newfoundland, with a maximal amplitude of the SST variation about 0.2 K. Figure 5b shows the situation 4 years later (nearly a quarter period). The anomaly of the SST south of Newfoundland is reduced and underlines the standing character of the oscillation in this part of the North Atlantic. Furthermore, a warming of the SST was detected in the center of the North Atlantic area. This suggested locally different processes for the development of the SST anomaly.

The balance equitation for the surface energy budget is given by:

$$\frac{\Delta H}{\Delta t} = F_{rad}^{sfc} - F_{SH}^{\uparrow} - F_{LH}^{\uparrow} - F_{G}^{\downarrow} - F_{M} - F_{Mix} - F_{A} \qquad (2)$$

Where F_{rad}^{sfc} denotes the net radiation flux, $F_{LH}^{\uparrow}$ and $F_{SH}^{\uparrow}$ the latent and the sensible heat fluxex, $F_{G}^{\downarrow}$ the heat flux into the subsurface layer, F_{M} the energy involved melting ice or in freezing water, F_{Mix} the horizontal mixing and F_{A} the heat transport due to the horizontal ocean current. To investigate the reasons for the locally different behavior of the SST only the latent and sensible heat fluxes, the horizontal temperature advection and the vertical temperature advection generated by Ekman pumping were considered. That means the temporal evolution of the SST is approximated by:

$$\frac{\partial T_s}{\partial t} + \vec{v}_h \cdot \nabla_h T_s + w_e \frac{\partial T_s}{\partial z} + \frac{1}{c_p \rho \Delta z}(F_{SH}^{\uparrow} + F_{LH}^{\uparrow}) = R\,, \qquad (3)$$

where the density (ρ) and the specific heat (c_p) are approximately constants. Δz is the thickness of the upper ocean layer (50m) and R stand for the residuum. In doing so, composite cycles were separately created for these fields.

Figure 6a and 6b show the results of the compositing for the region south of Newfoundland (40°-50°N, 55°-65°W). The vertical thermal advection of the ocean surface layer (diamonds) and the horizontal part of the advection (squares) leads the SST (circle) for one quarter period, suggesting an advective forcing. That is, an increasing SST is generated by a weaker subpolar Gyre and Labrador Stream and a weaker pumping as well as due to the anomalies of the SLP and corresponding anomalies of the windstress. The latent heat fluxes (square) and the sensible heat fluxes (diamonds) are in phase with the SST (circles) (a positive value denotes a flux into the ocean). An anomal warm SST simultaneously forces a higher heat flux into the atmosphere, i.e., in this area the SST anomaly is generated by the temperature advection and is damped by the turbulent heat fluxes.

In the center of the North Atlantic (35°-45°N, 45°-55°W) the anomal flux of latent heat (diamonds) into the ocean leads the SST (circles) by a one quarter period (Figure 7b). The influence of the sensible heat flux can be neglected (not shown), i.e., an increasing SST is primarily forced by an anomal high latent heat flux into the ocean. The horizontal (squares) and the vertical (diamonds) temperature advection is nearly in phase with the SST (circles) and tends to amplify the SST anomaly. (Figure 7a) Robertson (1996) found the same forcing of the SST over North Pacific region.

The anomaly of the ocean temperature in 150m depth has approximately the same spatial behavior as the SST. The maximal amplitude is slightly shifted south-east to the SST anomaly south of Newfoundland (not shown). Furthermore, a large extension of the anomaly is visible along the 40° N latitude. The subsurface temperature has approximately the same amplitude but it leads the SST anomaly in this region about two years and it is in phase with the SLP and geopotential height at 500 hPa. The temperature advection is in phase with subsurface temperature and tends to reinforce the anomaly. It is not clear what processes are responsible for an increasing sub surface ocean temperature in this region.

An anomalous 2 meter temperature south of Newfoundland is accompanied by an anomaly with a different polarity in the Baffinland area. It is obvious, that the 2 meter temperature over the North Atlantic yields the same spatial behavior as the SST (not shown). A reduced meridional gradient of the 2 meter temperature is found in a region where the strongest meridonal temperature gradient normally occurs in the North Atlantic area. The 2 meter air temperature and the SST are in phase and have the same amplitude caused by the short response time of the atmosphere due to SST changes with a timescale of only several days (e.g. Egger, 1977).

18 years mode over the entire Northern Hemisphere

This particular oscillation mode, isolated by Robertson (1996) over the North Pacific, has nearly the same period (of about 18 years) and a comparable SST and the geopotential height at 500 hPa variability like the interdecadal mode over the North Atlantic region presented here. This suggests a coupling of these two modes. To explore potential connection a combined MSSA was applied to the annuals means of the SST and of the geopotential height at 500 hPa over the entire North Hemisphere. Both variables were bandpass-filtered and pooled with a combined EOF analysis in same manner as described in chapter 3. The leading 30 PCs of the combined EOF analysis were the input channels of the MSSA (they explained about 10% of the total variance over the Northern Hemisphere). An oscillation with a period about 18 years can be detected. Figure 8 shows the pattern of the 500 hPa height at the very moment when the low pressure area east of Newfoundland reaches it peak. A strong atmospheric circulation over the Pacific leads about 5 years the atmospheric anomaly found over the Atlantic. The spatial struture of this mode is the same as the 18-year mode separately detected over the North Atlantic and the North Pacific. The pattern correlation of geopotential height between the local analysis and the analysis of the entire Northern Hemisphere is about 95% over the North Atlantic and about 93% over the North Pacific region. It is obvious that the atmospheric variability of this mode is concentrated in the midlatidudes. Figure 17 shows a Hovmöller-diagram for the first 150 years of the geopotential height anomaly averaged over the 30°N-60°N latitude range. An anomal behavior of the atmospheric circulation is not only confined over the ocean areas, it is also visible over North Russia (around 50°E longitude), but it disappears over the Asia Continent. Furthermore the standing character of the oscillation is underlined.

Table 1: Correlation between the different indices of the 500 hPa geopotential height over the North Pacific (40°-50°N, 165°-175E°) and over the North Atlantic (40°-50°N, 45°-55°W) for the local and the hemispheric analyses (* 5 and ** 4 years lagged correlation).

Geopotential height at 500 hPa		Local analyses		Hemispheric analyses	
		North Pacific	North Atlantic	North Pacific	North Atlantic
Local	North Pacific	1.00	0.55**	0.85	0.85**
Local	North Atlantic		1.00	0.72*	0.71
Hemispheric	North Pacific			1.00	0.95*
Hemispheric	North Atlantic				1.00

Table 2: Correlation between the different indices of the SST over the North Pacific (30°-40°N, 165°-175°E) and over North Atlantic (40°-50°N,55°-65°W) for the local and hemispheric analyses (* 5 and ** 4 years lagged correlation).

SST		Local analyses		Hemispheric analyses	
		North Pacific	North Atlantic	North Pacific	North Atlantic
Local	North Pacific	1.00	0.55**	0.86	0.86*
Local	North Atlantic		1.00	0.72*	0.73
Hemispheric	North Pacific			1.00	0.96*
Hemispheric	North Atlantic				1.00

The variability of the local analyses is all the time greater than for the analysis of the hemisphere. Table 1 shows the correlation between the different indices of the 500 hPa geopotential height over the North Pacific (40°-50°N, 165°-175E°) and over the North Atlantic (40°-50°N, 45°-55°) for the local and the hemispheric analyses and table 2 shows the same for the SST. The Index of the 500 hPa geopotential height of the local analysis over the North Atlantic is well correlated (about 70%) with the analysis over the entire Northern Hemisphere. A better correlation (about 85%) occurs the index of the North Pacific of the local analysis with the hemispheric one, whereas the time series of both local analyses are less correlated (about 50%). The same is true for the SST. These results suggest that the detected modes over the two oceans are coupled, but strong modulated by local processes over the North Atlantic and North Pacific area.

5. Conclusion and Discussion

An interdecadal oscillation in the ocean and atmosphere system was found in a 500 year integration of the coupled ocean-atmosphere circulation model ECHAM1/LSG. It shows a period about 18 years in a 10-50 year band over the North Atlantic. The most activity occurs around the year 200.

The detected anomaly of the SST was primarily generated by the thermal advection of the upper ocean layer. The horizontal part of the anomal advection was linked to strength and position of the subpolar gyre and the Labrador Stream propagation and the vertical part was essentially generated by Ekman pumping. Both processes, the gyre activity and the Ekman pumping vertical velocity, are forced by the anomaly of the windstress field. Thus the anomaly of the SST primarily reflects the passive response of the upper ocean layer of an atmospheric forcing. The turbulent heat fluxes damped the SST, except for the center of North Atlantic. Here the fluxes of latent heat force the SST anomaly and the thermal surface advection tends to amplify the anomaly.

The 2 meter temperature of the atmosphere and the SST are in quasi thermal equilibrium. An anomalous warm SST south of Newfoundland enhanced the meridonal gradient of temperature north of the anomaly in the ocean and atmosphere. Palmer and Sun (1985) showed, that the response of the atmosphere of such SST distribution is a northward shifted enhanced baroclinic eddy activity. This implies weaker westerly winds over the mid-latitude North Atlantic accompanied by a weaker low pressure area east of Newfoundland. Similar results were found by Latif and Barnett (1994) over the North Pacific area in a 70 year integration of the higher resolution (T42) ECHO model, although in the presented results the geopotential height at 500 hPa and the SLP leads the SST by 2 years. Robertson (1996) found the same behavior of the 18 year mode for the North Pacific. Here the 500 hPa geopotential height leads the SST about 1 year. Nevertheless, this suggests that changes in meridonal temperature gradient in the midlatidudes accompanied by a modification of the baroclinic eddy activity, at least, has an affect on here presented atmospheric fluctuations. These results are inconsistent with classical linear theory where a heating by anomal warm SST in the midladitudes accompanied by a surface anticyclone is shifted westward to the heat source (e.g. Hoskins and Karoly, 1981 and Egger, 1977).

The area of the maximal amplitude of the 150m ocean temperature anomaly is situated south of Newfoundland. In this area a anomal cold subsurface ocean layer at 150m is in phase with the anomal strong atmospheric circulation and leads the maximal of the SST anomaly about 2 years. Robertson (1996) found the same behavior in the area (140°E-160°E, 25°N-35°N).

The 18 year oscillation can be found over the whole hemisphere and is concentrated in the midlatidudes. The 500 hPa geopotential height anomaly is pronounced the most over the North Pacific and North Atlantic but it is also visible over North Russia. This hemispheric mode is well correlated with the isolated oscillations of the local analysis over the North Atlantic and North Pacific sector. The amplitude of the geopotential height and the SST anomalies of the analysis of the entire North Hemisphere are weaker than the two local analyses but in a good temporal agreement.

Based on our findings we may conclude that the North Pacific and the North Atlantic mode are coupled and may have not their origin in an air-sea interaction over the North Pacific or North Atlantic alone, but with a strong modulation due to local processes. This is at variance with Latif and Barnett (1994), who supposed that the interdecadal variability over North Pacific based on an unstable air-sea interaction between the gyre strength and the Aleutian low pressure system. Further investigations are required to obtain the driving mechanisms of the interdecadal fluctuations of the atmospheric circulation.

The isolated oscillation mode presented here has nearly the same period to that Zorita and Frankinoul (1996) detected in a 325 year integration of the same GCM, but the spatial and temporal behavior differs from the results presented here. In contrast to our investigation, the authors found that the SST modulation by the gyre current was weak. They also found no evidence for an air-sea interaction as the reasons of the interdecadal variability over the North Atlantic.

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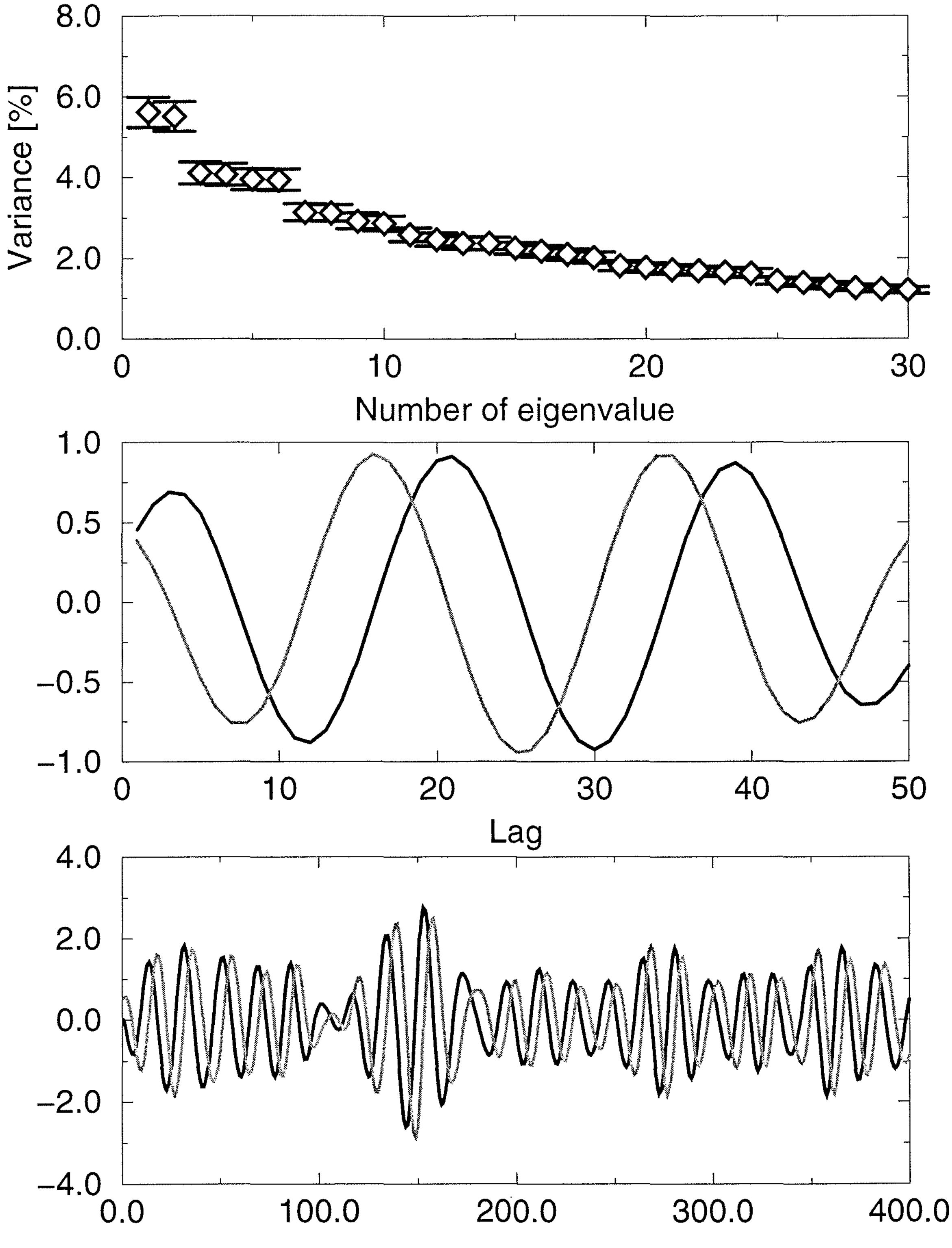


Figure 1: Combined 11-variable MSSA over the North Atlantic area (a) Eigenvalue spectrum, (b) the first channel of the corresponding ST-EOF to the leading pair of eigenvalues, (c) as (b) but the corresponding ST-PC

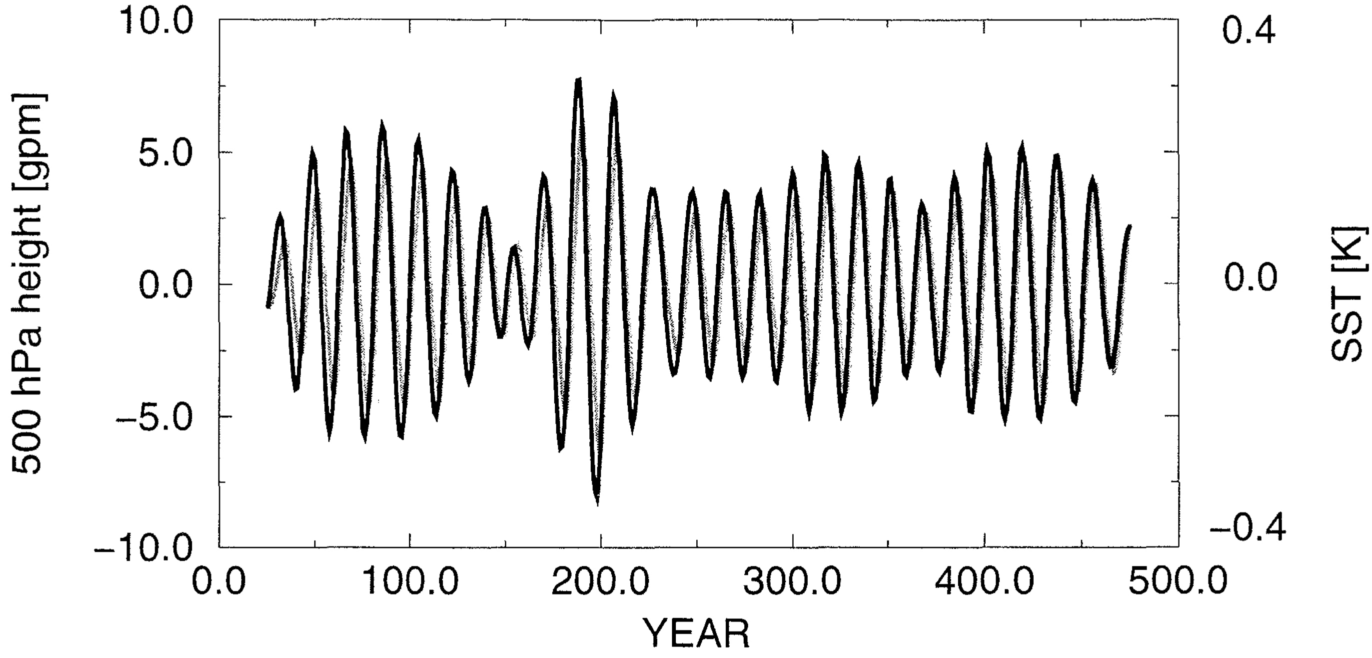


Figure 2: Indices of spatial averages of the RCs for the SST south of Newfoundland (40°-50° N, 55°-65°) (gray line) and the geopotential height at 500 hPa east of Newfoundland (40°-50° N, 45°-55°) (black line).

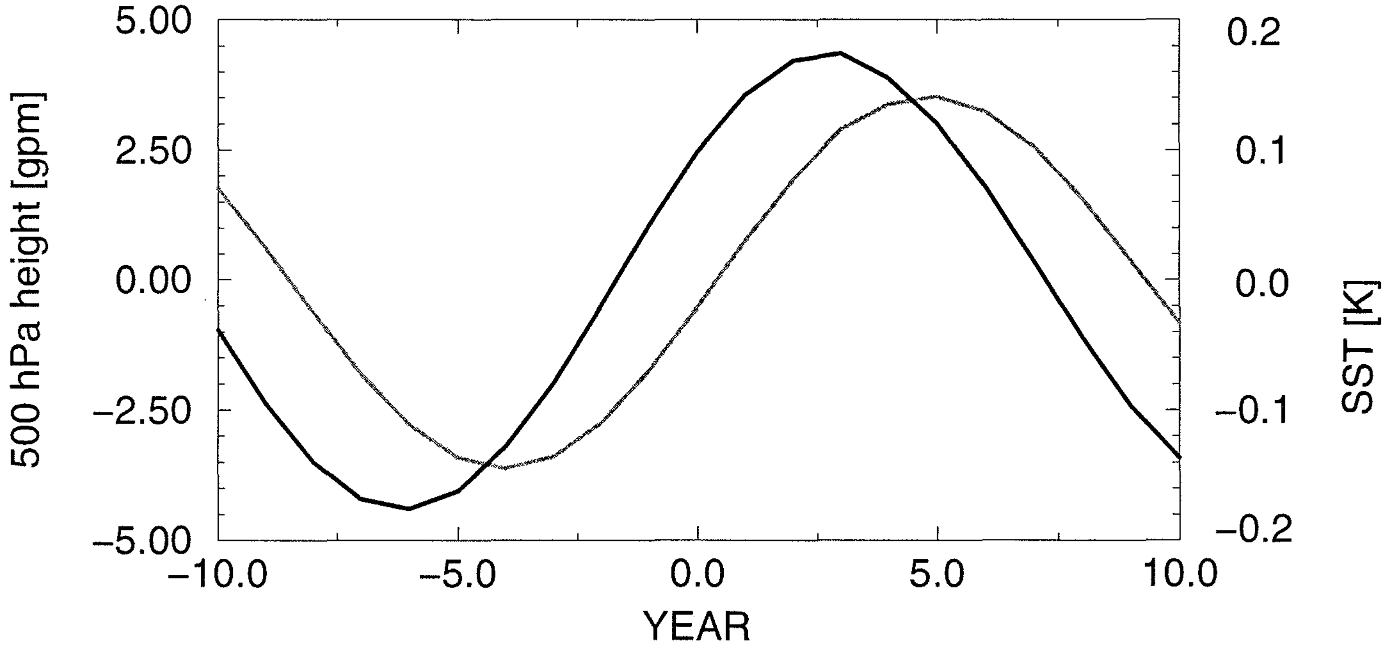
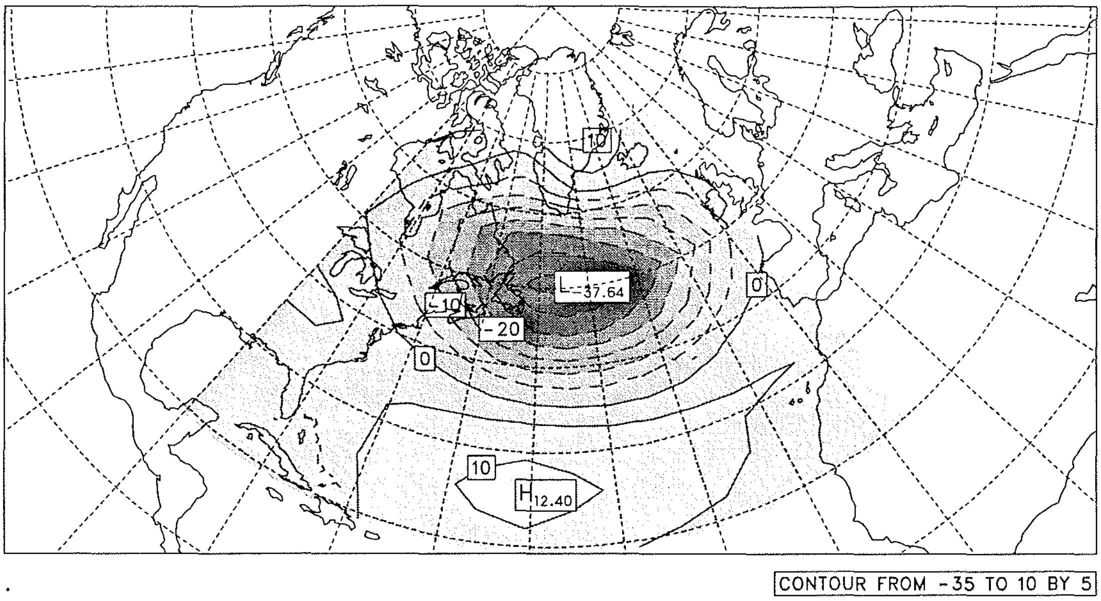


Figure 3: Composite cycle of the SST (gray line) and 500 hPa geopotential height (black line) for the same region as figure 2.



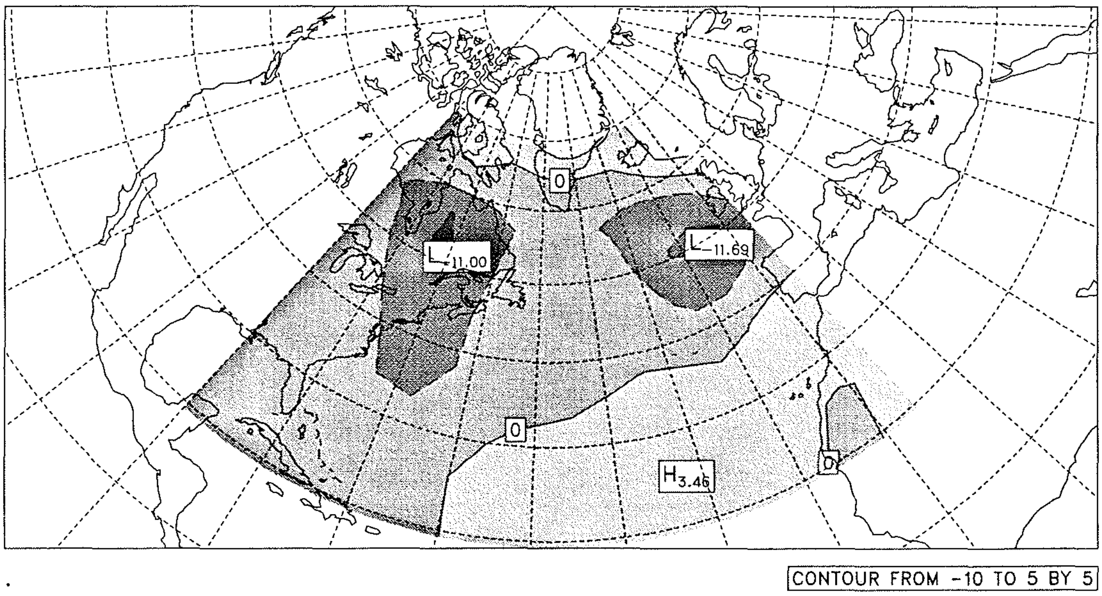
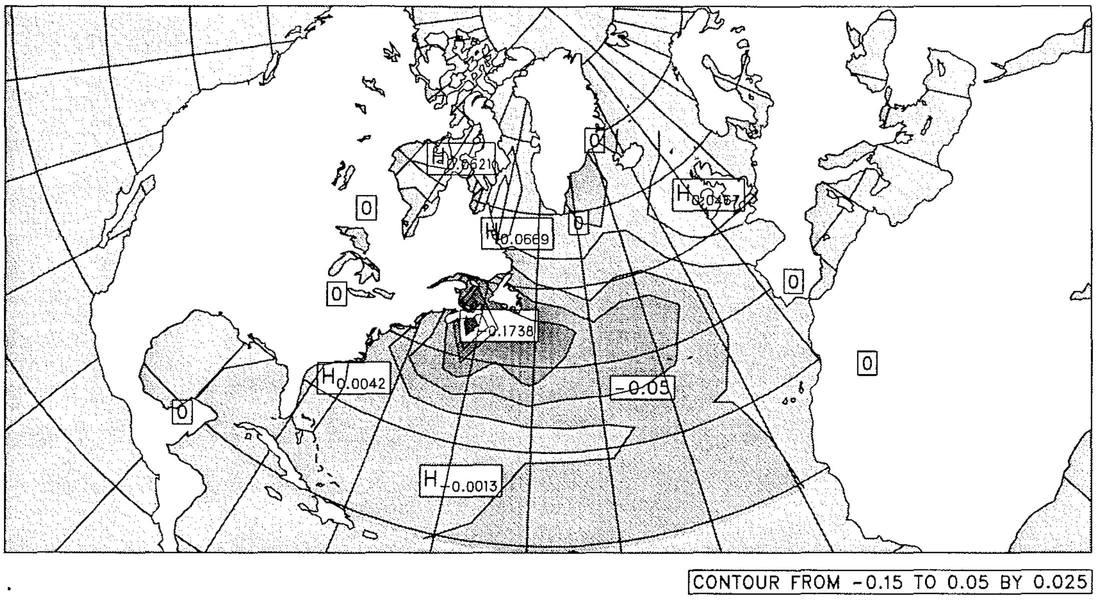


Figure 4: Composite maps of the SLP (a) at year -6 (two years before the SST reaches its negative peak south of Newfoundland, (b) four years later. Negative values dashed



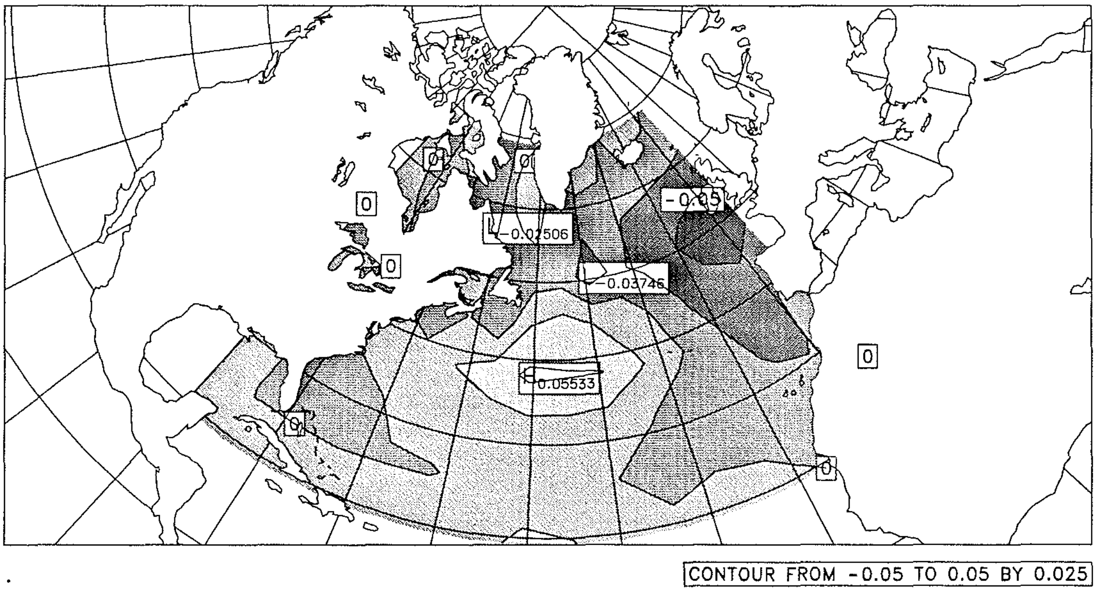


Figure 5: Composite maps of the SST, (a) at year -4 and (b) five years later

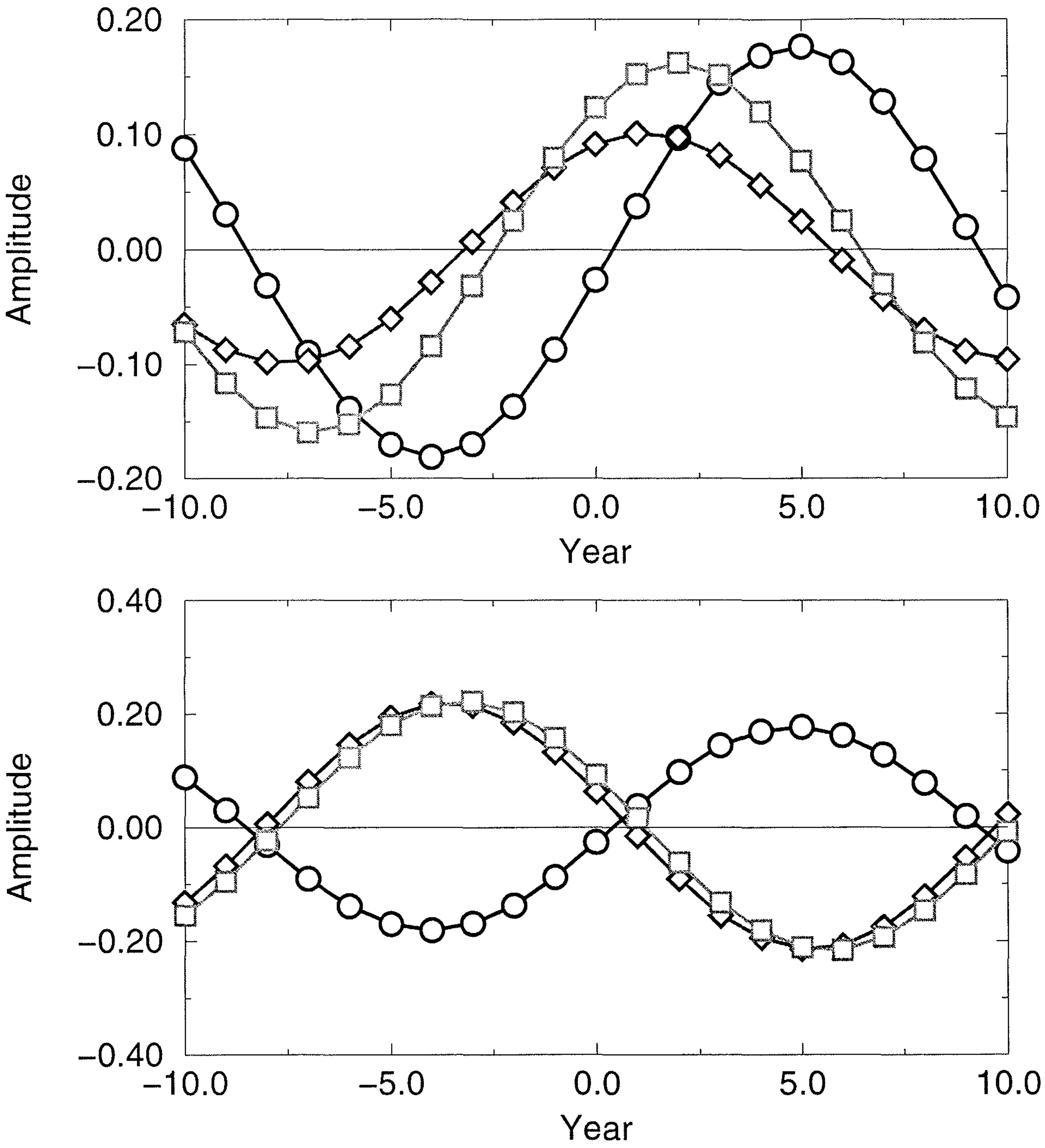


Figure 6: Composite cycle for region east of Newfoundland. (a) SST [K] (circles), vertical thermal advection generated by Ekman pumping [K/a] (diamonds) and horizontal thermal advection [K/a] (squares), (b) SST [K] (circles), fluxes of latent heat [K/a] (diamonds) and the fluxes of sensible heat [K/a] (squares).

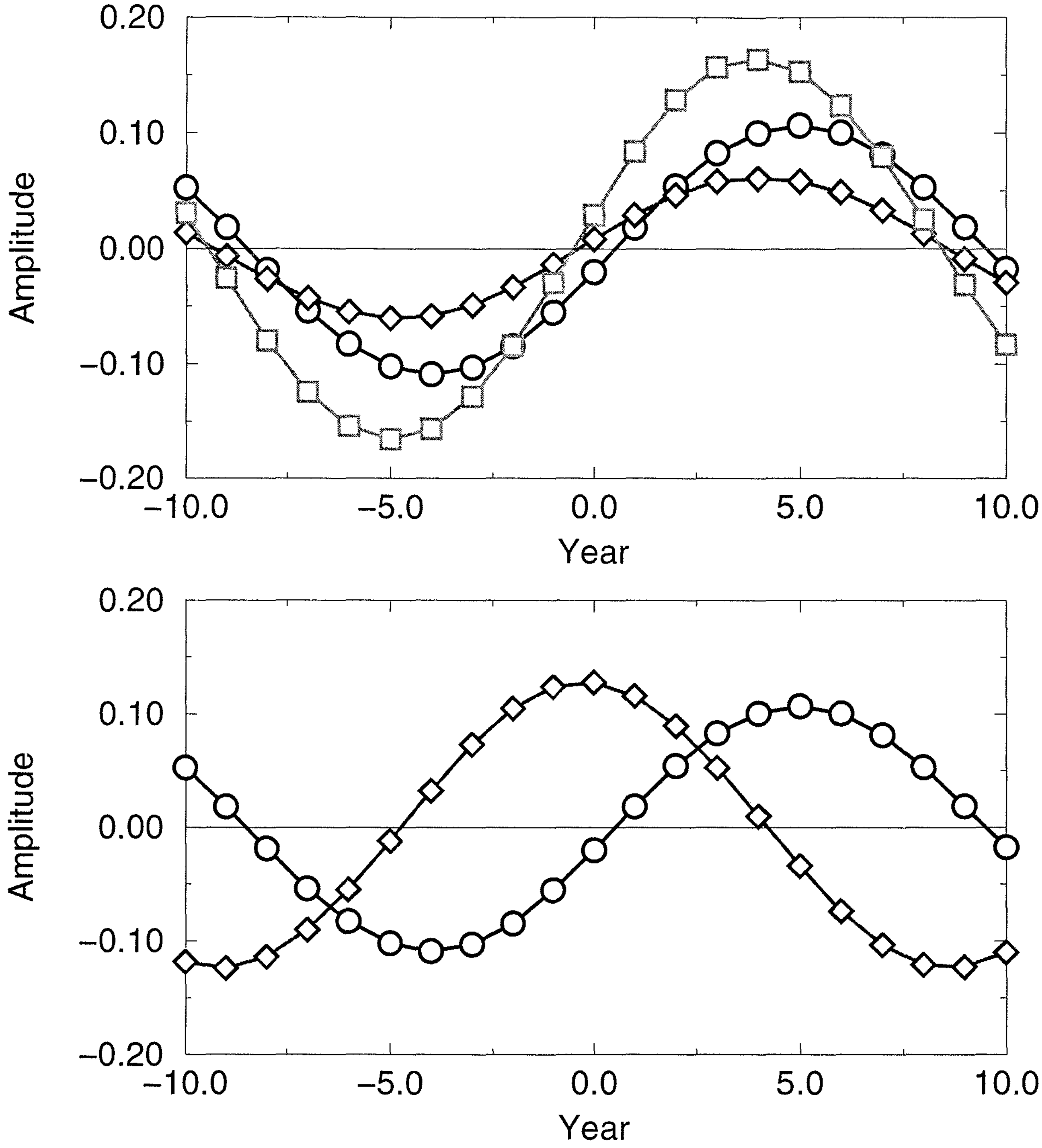


Figure 7: Composite cycle over the area (35°-45° N, 45°-55° W). (a) SST [K] (circles), vertical thermal advection generated by Ekman pumping [K/a] (diamonds) and horizontal thermal advection [K/a] (quares), (b) SST [K] (circles), fluxes of latent heat [K/a] (diamonds).

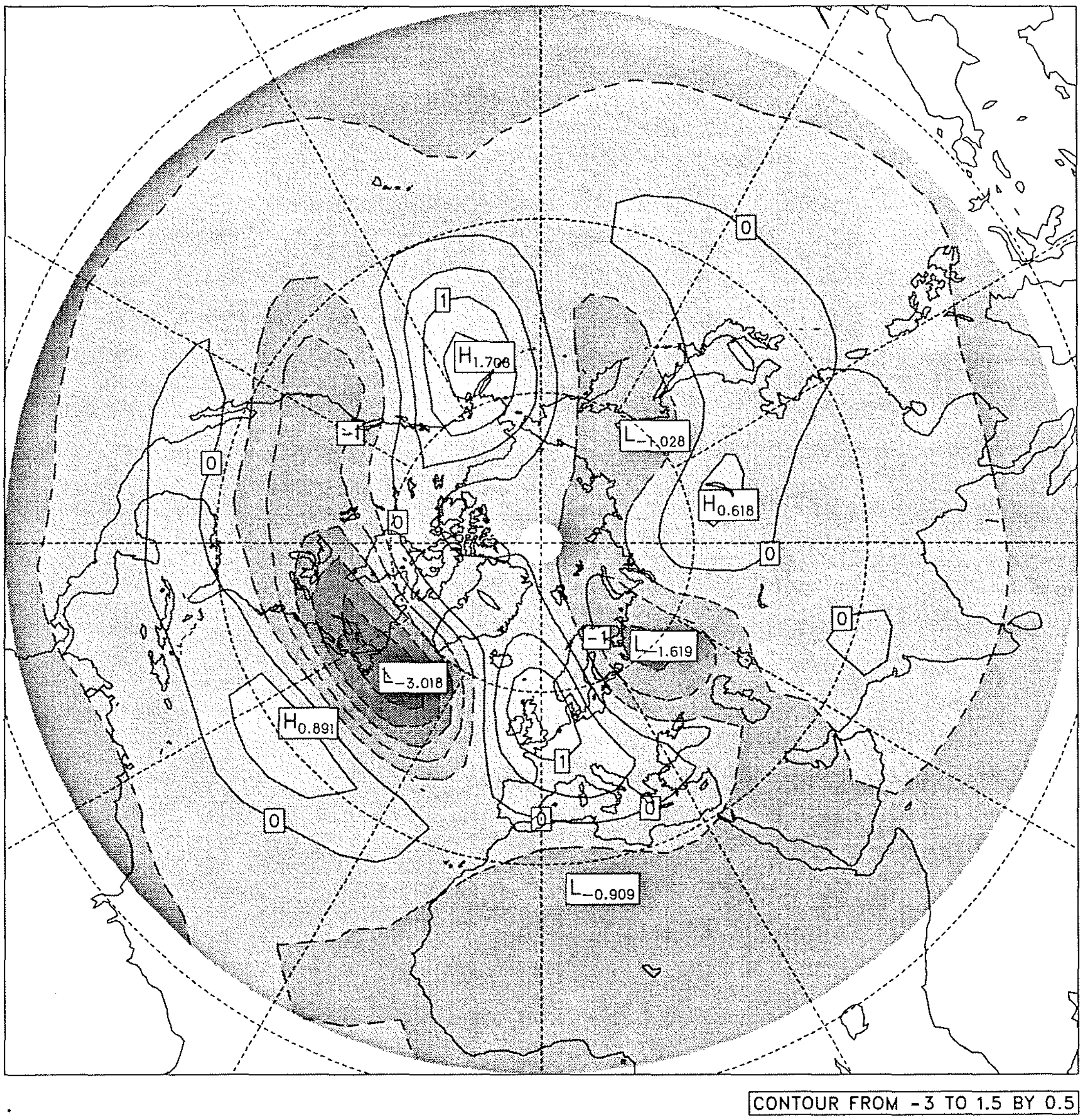


Figure 8: Composite maps of the geopotential height at 500 hPa over the Northern Hemisphere, at the moment when it peaks in the area (40°-50° N, 45°-55° W).

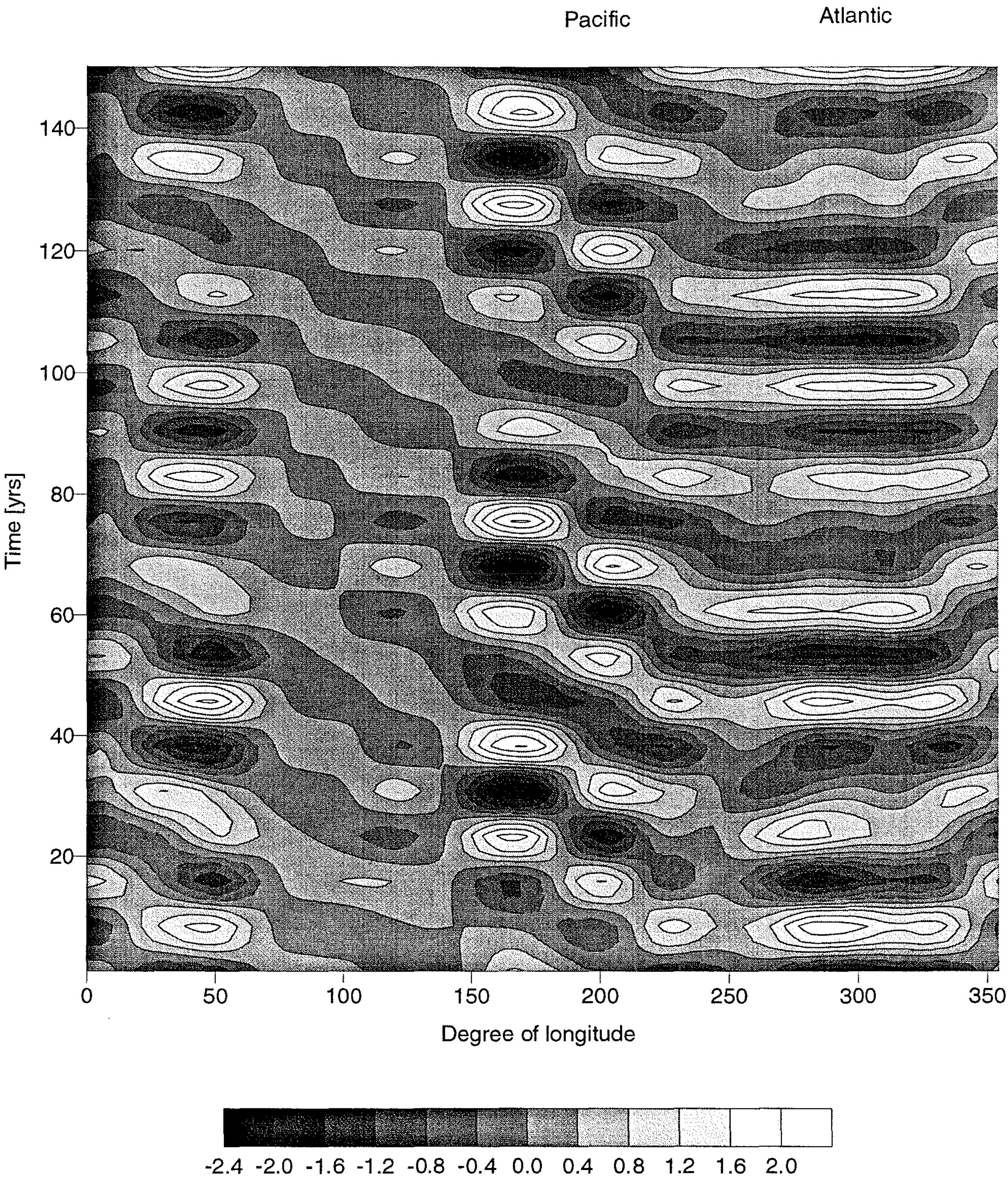


Figure 9: Time-longitude cross-section for the first 150 years of the geopotential height anomaly averaged over the 30° N - 60° N latitude range.